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A concept for a pallet configuration approach using zero-point clamping systems

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Abstract

Flexible Manufacturing Systems (FMSs) consist of machine tools capable of executing a wide range of machining operations relying on the fixtures to reference and block the parts. Hence, the constraints for their flexibility are shifted from the machines to the pallets. An interesting trend in the fixture market are zero-point fixture systems grounding on a clamping system that can hold standard baseplates where the fixture has been previously mounted. This allows a rapid and safe exchange of the baseplates without the need of realignment between the modular fixture and the pallet. In this paper we present an approach for rapid pallet configuration that exploits the additional level of flexibility provided by zero-point fixture systems. Grounding on an ontology-based data model, the description of the production process as a Network Part Program is used to evaluate the impact of rapid pallet configuration at system level and also how these degrees of freedom can be used in the management of the system. The steps of the approach are tested against a real industrial case provided by a company owning an FMS.

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Keywords: FMS, pallet configuration, fixturing.

1. Introduction and Problem Statement

Today's manufacturing systems face the challenge for quick reconfiguration at a minimal cost, while adapting to a market demand that may range from high to small volumes and from mass production to mass customization. Moreover, newly introduced product models, new model variants, new materials, new processing technologies, as well as unexpected internal and external events, entails the need of adapting the behaviour of a manufacturing system to the evolving conditions. This need of continuous adaptation has been identified with the concept of co-evolution, i.e., the joint evolution of the characteristics of different aspects in a production system, typically the products, the processes and the production system itself [1]. To manage co-evolution, *change enablers* must be embedded in the production system to support the modification of its structure and capabilities when needed [2].

Flexible Manufacturing Systems (FMS) represent a production system architecture that provides several change enablers since it is usually adopted to tackle a demand characterized by a large part mix in small quantities. Indeed, these systems incorporate automation, sensors, numerical control, programmability, etc., to execute a wide range of machining operations. The level of flexibility has increased significantly in modern FMSs that are usually programmable, equipped with automatic devices for tool and part changing and characterized by a working area in which they can provide their capability. However, the potential flexibility of an FMS is still constrained by the interaction between the system and the physical characteristics of the parts. Indeed, every time a new part type must be put into production, or every time an already existing part type is modified or must be machined in a different way, the fixtures must be properly designed, thus significantly limiting the *mobility* [17] of the FMS flexibility in the short-term period. With the goal of reducing setup times, FMSs use pallets to host parts, entailing the capability of operating the setups needed to manage different parts outside of the system.

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The market trend of reducing the lot sizes and increasing the product variants and modification leads to the need of a high number and type of fixturing devices to better exploit the flexibility of the machines in an FMS. To tackle these requirement, a different kind of modularity can be exploited through *zero-point clamping technologies* (Figure 1) consisting of a clamping system that can hold standard baseplates where the fixtures have been previously assembled and verified.

The clamping system assures that, as the baseplates are changed, the fixtures do not need to be realigned for the correct positioning of the parts. Hence, they provide constant zero point without the need of realignment between the modular fixture and the pallet, while guaranteeing a rapid and safe exchange of the fixtures.

An additional consideration is due in relation to the use of zero-point clamping systems to enable a fast pallet reconfiguration. As shown in Figure 2 these systems also provide pallet tombstones onto which different baseplates can be assembled and, by varying the type and position of the baseplates, also the pallet configuration can be changed. These fixtures are an important *enabler for reconfiguration* in an FMS. Indeed, since the pallet does not need a realignment of the fixtures upon a reconfiguration, it can be modified very quickly, even while the system is working. This opportunity, together with the capability of assembling fixtures hosting different part types on the same pallet, is extremely relevant at the planning and manufacturing execution levels.

Figure 1. Zero-point clamping system (courtesy of Schunk)

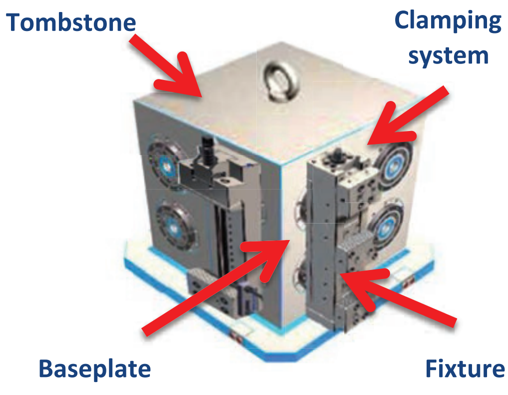

Figure 2. Modular pallet configuration using zero-point clamping systems

Specifically, Sect.2 introduces a data model that can be employed to store information related to the parts to machine and the associated machining process as well as the available pallet configurations in terms of tombstones, baseplates and fixture elements. Then, Sect.3 presents a pallet configuration approach to support the recurrent reconfiguration phase. In addition, Sect.4 gives an outline of the exploitation of these devices at the system management level. Finally, an application to an industrial case is described to demonstrate the viability of the technologies and the associated approach.

2. Data Model

The use of zero-point clamping system for fast pallet reconfiguration aims at addressing the co-evolution of products, processes and production systems. This entails the need of a shared data model to provide information in relation to the workpieces, the machining process and the viable pallet configurations. Existing technical standards and research efforts have been selected and extended to be used in a ontology-based platform exploiting semantic web technologies. This platform aims at supporting the interoperability between the various software tools that are used during the business processes related to the design and management of an FMS, e.g. process planning, pallet configuration (see Sect. 3), FMS design [16], FMS management (see Sect. 4), and FMS monitoring [20].

The semantic web approach enables a smooth integration and extension of heterogeneous data models. In accordance with the strategy of knowledge re-use, the data model developed for flexible production systems stems from previous results in the literature and represents an enhancement of the an OWL ontology [15] named Virtual Factory Data Model (VFDM) [3]. The VFDM aimed at formalizing the concepts of building, product, process and resource while taking into consideration geometric, physical and technological properties of the factory that are required to support its planning processes. The VFDM exploited already existing technical standards for manufacturing, thus trying to favour the interoperability between software tools. In particular, the Industry Foundation Classes (IFC) [14] by buildingSMART was the main reference standard. However, the VFDM did not consider the fine grained aspects of pallet configuration and therefore a proper extension was needed to satisfy the semantic representation of: (1) the workpiece and its features, operations, and setup (Sect. 2.1); (2) pallets and fixture elements (Sect. 2.2); (3) the visual inspection system and the output of the pallet visual check activity (Sect. 2.3).

The architecture of the resulting data model (Figure 3) consists of the following modules:

- *IFC_ADD1*, ontology (named also *ifcOWL*) that is automatically converted from the IFC standard in EXPRESS language to OWL [10][11].
- *ifcOWL_rules*, a module defining additional class expressions to represent some of the WHERE rules that are found in the IFC EXPRESS standard [12].

- *StatisticsOntology*, a novel ontology defining basic concepts about probability distributions and descriptive statistics.
- *fsm*, an ontology for finite state machine in the form of statechart [7] by Dolog [13].
- *FsmExtension*, a module providing extension to the basic representation of a finite state machine.
- *ifcOWL_extensions*, module representing the integration of the *FsmExtension* module and the *ifcOWL_rules* module, by linking the concept of finite state machine with the object defined according to the IFC standard. In addition, this module extends the IFC ontology by defining the history of the objects [8].
- *ISO14649-10*, module that represents a fragment of the STEP-NC standard [9] automatically converted into an ontology.
- *FO1.3*, FixOnt ontology on fixtures by Gmeiner and Shea [4].
- *VisualInspectionDomain*, novel module representing visual inspection systems and reports.
- *FactoryDomain***,** module that specializes the classes of the IFC standard by introducing the concepts like production process, part type, manufacturing system, machine tool.
- *DiscreteManufacturingDomain*, module that integrates four modules (*ISO14649-10*, *FO1.3*, *VisualInspectionDomain*, *FactoryDomain*) and provides further specializations for the industrial domain of discrete manufacturing.
- *MachiningTaskType* that is a subclass of *machining_workingstep* from STEP-NC and *IfcTaskType* from IFC.

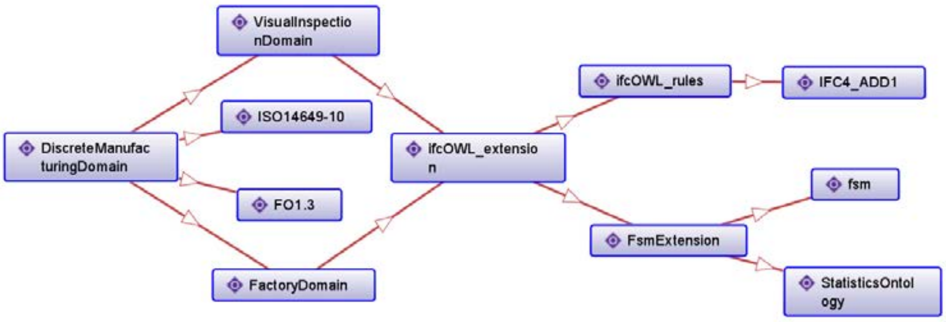

Figure 3. Overall Architecture of the data model

2.1. Workpiece and machining process

The standard *STEP-NC part 10* [9], available as an EXPRESS schema, was chosen to represent the workpiece and its operations. The object and feature-oriented STEP-NC standard is designed to describe the machining operations executed on a workpiece. Thus, STEP-NC machining model includes geometric dimension and tolerance data for inspection. The product description of the machined part is connected to the computer numerical controlled machining operation data using the object-oriented concept of working steps. These working steps correspond to associated process parameters as well as high-level machining features.

The EXPRESS schema of STEP-NC was automatically converted to an OWL ontology by exploiting the work by Pauwels and Terkaj [10] and then a fragment of the ontology was extracted to represent the key concepts of workpiece, manufacturing features, machining operations, and machining workingsteps.

The integration between the IFC and STEP-NC standards was realized by creating the following new classes:

- *WorkpieceType* that is a subclass of *workpiece* from STEP-NC and *IfcTypeProduct* from IFC.

2.2. Pallet and fixtures

The formalization of the fixture elements grounds on the FixOnt ontology [4] that classifies workholding fixtures and fixture components. The development of FixOnt was motivated with the demands for a formal model that can support an automated process of fixture design as well as automated reasoning in a reconfigurable manufacturing system [4]. FixOnt reuses and adapts the FIXON ontology [5], including several extensions of the relevant segments.

Herein, a fragment of the FixOnt ontology was integrated with the IFC standard by defining the class *FixtureComponent* from FixOnt as a subclass of *IfcElement* from IFC. The class *FixtureComponent* is specialized by several classes to represent the possible elements in an assembled fixture (e.g. clamp, fastener, jaw, tooling plate).

Furthermore, novel classes were defined in the *DiscreteManufacturingDomain* module. The class *Pallet* represents the concept of pallet, whereas *WorkholdingPallet* is a specific pallet associated with the definition according to ISO8526 standard. Finally, the class *FixturingFace* was introduced to represent the area (or sub-area) on a configured pallet that can be used to mount and clamp the workpieces to be processed.

2.3. Visual Inspection

The *VisualInspectionDomain* module contains the definition of the class *Scanner3d* representing a generic device that can be employed for a visual inspection. The class *Scanner3d* is specialized by class *LaserScanner*, i.e. a tool composed by a laser source and a camera. All these classes are defined as subclasses of *IfcElement* from the IFC standard.

Furthermore, the class *VisualInspectionReport* represents the information in a visual inspection report and is related to *VisualInspectionSetup* class to define the setup of the visual inspection, i.e. which is the object to be inspected and which visual inspection device must be used.

The history of a pallet (but also a generic element) can represented by the *IfcElementHistory* class being a subclass of *IfcProductHistory* proposed in [4]. In principle, any physical element can be inspected, therefore *IfcElementHistory* is related to VisualInspectionReport class to enable the tracking of the visual inspections during the lifecycle of an element, thus exploiting the concept of history as suggested in [8].

3. Pallet Configuration

The traditional goal of a pallet configuration approach is to provide a pallet design given a set of workpieces, the associated setups and the machining operations to be executed. The configuration approach must be able to assess the machinability of the operations in the assigned setups, according to the capability of the machine tool [21]. A pallet configuration is designed every time a new workpiece must be put into production, or every time a modification of the existing configurations is needed. Taking advantage of the zero-point clamping system to enable a fast reconfiguration of the pallets entails the need of a fast and viable approach to design new pallet configurations on a regular basis.

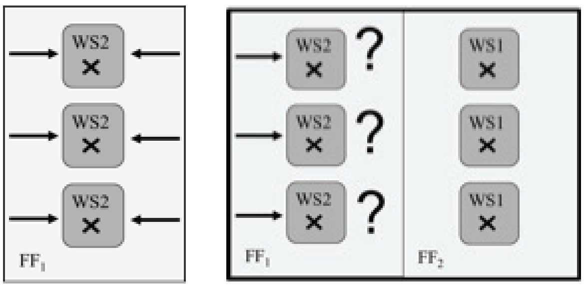

Figure 4. Example of setup accessibility.

Here we present an approach aiming at providing an optimal pallet design in terms of number of finished workpieces, saturation and balancing of the pallet.

The following hypothesis are considered:

- the possible pallet tombstones has a square or a cubic shape;
- each pallet provides a given number of fixturing faces, i.e., physical faces where the parts can be mounted (e.g. a cubic tombstone provides four fixturing faces, a square tombstone two);
- each fixturing face can be partitioned into sub-faces. Each sub-face is rectangular and is characterized by its position and its two dimensions.
- each sub-face is characterized by a workpiece pattern, i.e. the number of rows and columns of workpieces.
- only four-axis machine tools are considered.

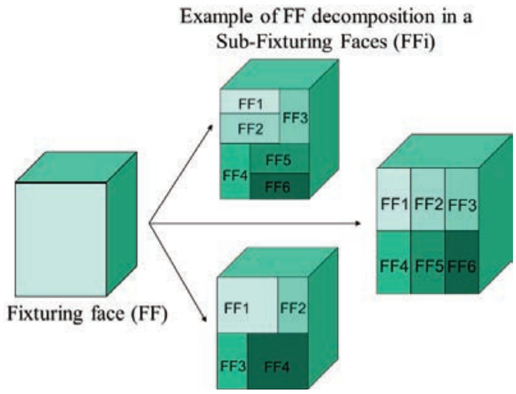

Figure 5. Fixturing faces.

The approach is based on three different activities: the verification of the setup accessibility, the pallet design optimization and the verification of its machinability.

3.1. Setup accessibility

Each setup is characterized by an orientation of the workpiece in the fixturing system and a set of reachable machining workingsteps (MWS) (whose tool access direction – TAD – results to be free once the workpiece is blocked in the setup orientation/position). Setup accessibility aims at analyzing possible changes in the visibility of the TAD of the setup on the basis of the position of the workpiece in the face, the patterns of the workpieces in the same setup and the patterns of the adjacent workpieces. If the TAD of one setup operation results to be unreachable, the setup accessibility is no more granted and the solution should be discarded. The TAD accessibility is evaluated through the kinematics study of the machine tool on which the pallet is going to be machined and represents an input for the pallet design optimization activity.

3.2. Pallet configuration

A mathematical model is used to define a set of alternative pallet configurations for the machining of different part types on a preselected pallet structure. The pallet structures can differ in terms of dimensions, number of available faces, decomposition in fixturing faces. For instance, **Error! Reference source not found.**XXX presents different pallet decompositions leading to different pallet design.

The idea underlying the developed mathematical model is to maximize the number of finished part per pallet, while maintaining the balancing of the pallet and granting the operation accessibility. Additional constraints are employed for the obtainment of alternative solutions in terms of pallet balancing and workpiece positioning. Finally, a set of constraints grant the coherence among the model data and variables. The described model is a mixed integer mathematical programming model solved using Cplex (IBM).

3.3. Pallet machinability

The machinability of a pallet on a set of machine tools is addressed. Since no specific information of the machining operations is known (e.g. torque, required power, deriving roughness), the check will be limited to the dimensions of the configured pallet in relation to the working cube of the considered machine tools. The time needed to completely machine a pallet on the set of selected machine tools is given.

Since during process planning the information on the configuration of the system machine tools is unknown, machining times are evaluated under the hypothesis that the pallet is processed on a single machine tool. In other words, the pallet will visit only one machine so that all the mounted workpiece will be completely machined. In details, MWS linear sequence is generated minimizing firstly tool changes, secondly axis rotations and finally movements among workpieces.

Once generated a feasible sequence, times necessary to move between every couple of MWSs that are one after the other in the sequence are estimated. Pallet machining time results in the sum of estimated rapid times and MWS productive times, while throughput is evaluated on the basis of pallet machining time and the number of finished workpiece per pallet.

4. Machine loading

Traditionally, pallets in a FMS are used to host a specific set of fixturing elements and, consequently, a given set of workpieces. As described in Section 1, this often constitutes a limit to the capability of a system to manage a rapid changeover of the parts. To overcome these limitations modular fixtures has been introduced, whose modules can be reconfigured and reused when the parts to be machined change. However, the assembling of modular fixtures onto a pallet and the need of checking the correct assembly to avoid the misalignment of the part requires a not negligible amount of time and effort. Due to this, fixtures reconfiguration has never been considered from an operational point of view. On the contrary, zero-point clamping systems significantly shrink the pallet configuration time and, hence, these reconfiguration actions can be used on a regular basis to match the varying production needs.

New loading policies must be developed to assign the machining operations to the available machines, taking into consideration the constraints imposed by the limited availability of tools, tool slots in the machining centers as well as their time availability in the considered time horizon and, at the same time, planning the reconfigurations of the pallets. Different configurations are taken into consideration and assigned to the different time periods to adjust utilization of the machine tools and the routings.

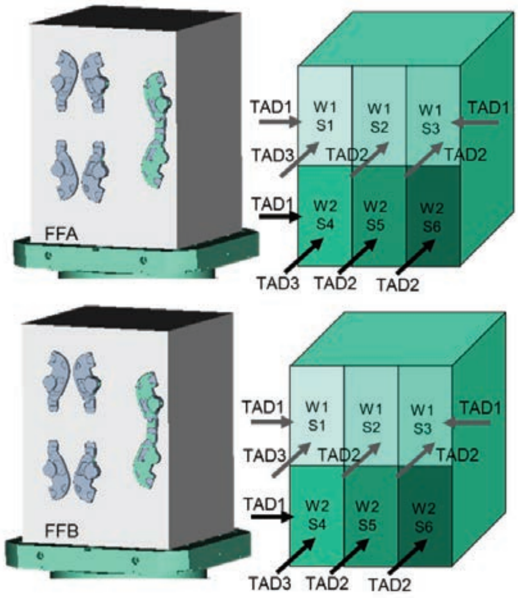

Figure 6. Alternative pallet configurations.

5. Industrial case

The described workflow has been tested on an industrial case provided by the Italian company Cembre S.p.A (http://www.cembre.it/). Cembre S.p.A. is a leading manufacturer of electrical connectors, crimping & cutting tools, railroad products, identification & labeling systems. It produces hundreds of part types, the majority of which is subject to high fluctuation of the demand, thus, pallets are periodically reconfigured.

In the current situations, the pallets are reconfigured using a mechanical system, hence, the reconfiguration requires a not negligible time. Moreover, the reconfiguration of the pallet is operated to spare the total number of tombstones in the system, i.e., a given tombstone is assembled according to a specific configuration from a predefined set.

Due to this, the campany does not reshape the available pallet configurations to match the fluctuation of the demand, e.g., reduce the number of faces devoted to a given part as its demand decreases. In these cases, the pallet is partially loaded, entailing a sub-optimal utilization of the available equipment (both the fixtures and the machine tools),

Hence, the described industrial cases perfectly fits the needs addressed through the proposed approach, leading to the need of methods and equipment to support the fast reconfiguration of the pallets.

Two different part types (W1 and W2), have been analyzed. They present 42 and 34 MWSs, 3 tool access directions (TADs) in the workpiece reference system (W1: –X, -Z, Z; W2: – Z, -Z, X) and 3 setups each (W1 - S1, S2, S3; W2 – S4, S5, S6). They are machined in three setups each.

The two workpieces are currently machined on a single pallet type hosting all the setups on a single face (Figure 7).

The described data model has been instantiated using the data coming from the industrial case, specifically the geometry of the parts, the machining process, the configuration of the pallet in terms of the tombstones and the different clamping elements hosted on it.

Starting from the geometry of the parts and the associated machining process, the pallet configuration approach has been used to provide a set of optimized pallet configurations exploiting the capability of zero-point clamping systems. Two of the viable configurations are illustrated in Figure 8.

Figure 7. Current pallet configuration.

In addition, the performance of the FMS under different loading policies have been evaluated, considering both the assignment of the operations to the machine tools as well as a reconfiguration plan for the available pallets. Specifically, the performance evaluation demonstrated that the introduction of the zero-point fixturing system entailed a reduction of the total number of pallets needed of about 25%. the total number of pallets needed in the production system, However, it must be noticed that the cost of the considered equipment is significant and, hence, its adoption is advised in particular for high variety of part types and very small lots.

Acknowledgements

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